the Energy to Lead

Pre-combustion Carbon Capture by a Nanoporous, Superhydrophobic Membrane Contactor Process

DE-FE0000646

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NETL CO_2 Capture Technology Meeting

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Introduction to GTI and PoroGen

- Not-for-profit research company, focus on research, development, and training needs of the natural gas industry, transportation, and energy markets

- Materials technology company commercially manufacturing products from specialty high performance plastic PEEK (poly (ether ether ketone))
- Products ranging from membrane fluid separation filters to heat transfer devices

Overall Budget

- Total Budget: $1.27MM Federal $1.0MM, Cost Share $276K (20%)
- Actual Spending: Federal $842 K, Cost Share $182 K (18%)

Performance Period

- October 1, 2009 – March 31, 2012

Performance as of July 31, 2011

- 8 of 10 Milestones Achieved

Participants

- Gas Technology Institute
- PoroGen
- Aker Process Solutions

Project Objectives

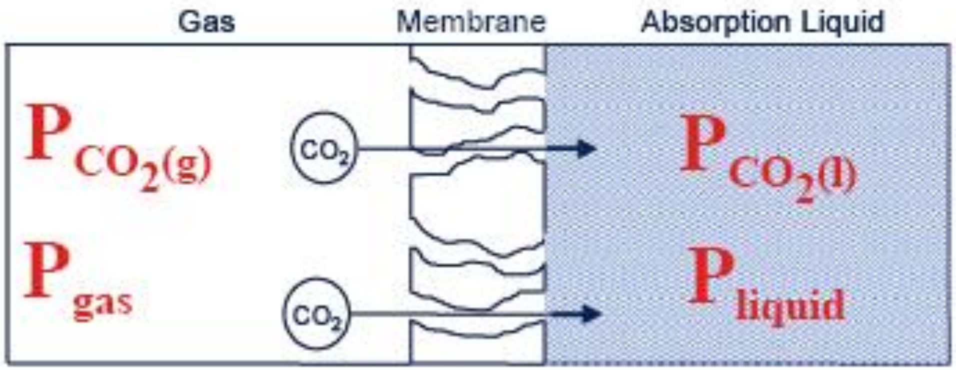
- **Project Objective:**
  - Develop a practical, cost effective technology for CO_2 separation and capture for pre-combustion coal-based gasification plants.
- **Key Developments:**
  - Highly chemically inert and temperature stable, super-hydrophobic hollow fiber membrane
  - Low cost integrated membrane absorber for CO_2 capture
  - Energy efficient CO_2 recovery process minimizing hydrogen loss

Technology Goals and Project Status

	Goal	Achievement
Separate and capture of the CO_2 from IGCC power plants	≥90% CO_2 capture	98% CO_2 capture
Increase in the cost of energy services	≤10%	14%
Apply gas/liquid membrane contactor concept while maintaining consistent pressures on both sides of the membrane	Membrane productivity for economic targets (mass transfer coefficient >0.1s^{-1})	Mass transfer coefficient:0.2 s^{-1}

What Is a Membrane Contactor?

High surface area membrane device that facilitates mass transfer



- Liquid on one side, gas on other side of the membrane
- Membrane does not wet out in contact with liquid
- CO_2 dissolved much more in the solvent, whereas H_2 to a much less extent
- Driving force is the difference in partial pressures of CO_2 $PCO_2(g)>PCO_2(l)$, $PCO_2(l)$ via Henry's Law Constant

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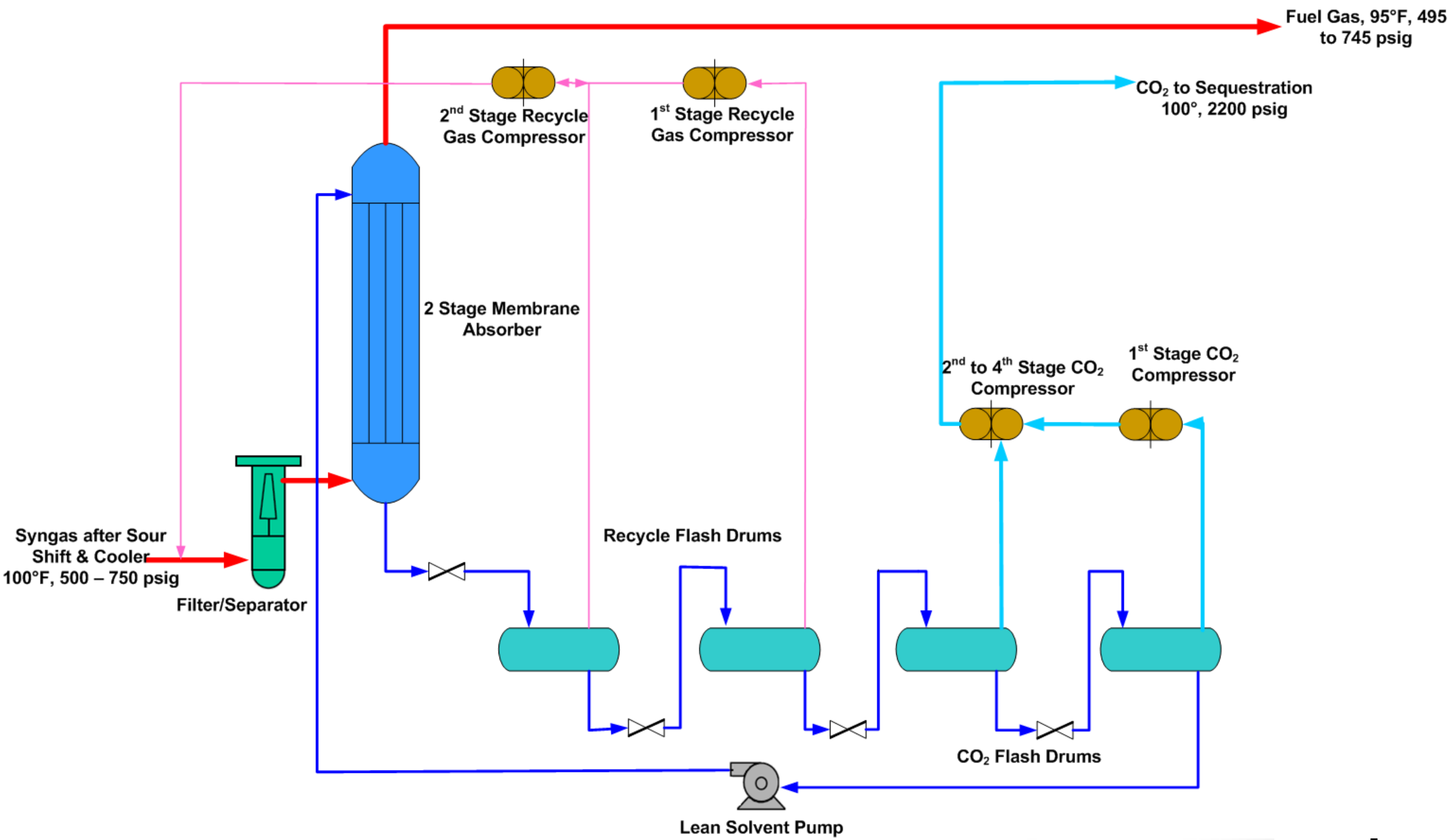
Simplified Process Flow Diagram and Process Conditions



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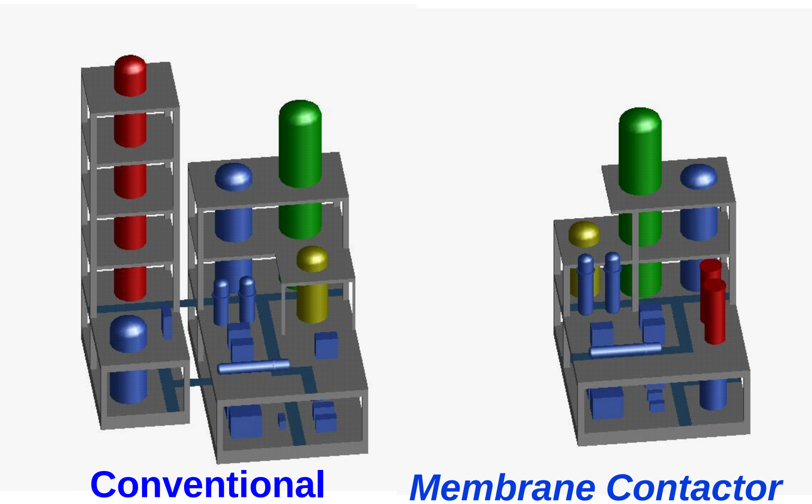
Membrane Contactor Has Technical And Economic Advantages Over Conventional Absorbers

Gas-liquid contactor	Specific surface area, (cm^2/cm^3)	Volumetric mass transfer coefficient, $(sec)^{-1}$
Packed column (Countercurrent)	0.1 – 3.5	0.0004 – 0.07
Bubble column (Agitated)	1 – 20	0.003 – 0.04
Spray column	0.1 – 4	0.0007 – 0.075
Membrane contactor	**1 – 70**	**>0.1**



Conventional Technology

Membrane Contactor as absorber

Reductions/Savings:

- •Capital Cost by 35 - 40%;
- •Operating Costs of 38% - 42%;
- •Dry Equipment weight of 32% - 37%;
- •Operating Equipment weight of 34% - 40%;
- •Total Operating weight of 44% - 50%;
- •Footprint requirement of 40%.

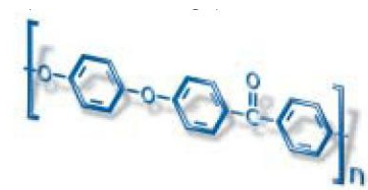
Data by Aker Process Systems

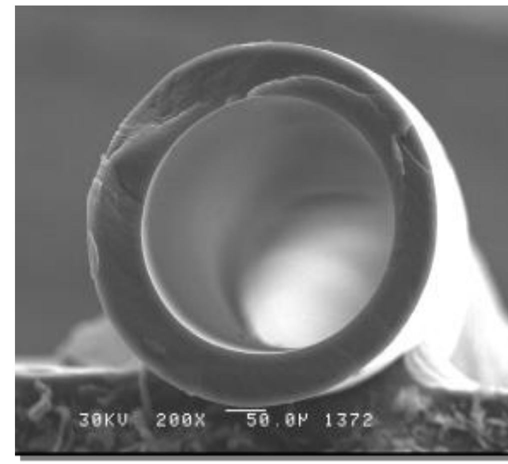
Contactor Technical And Economic Challenges

- Extraordinary number of modules need – Contactor performance
  - Minimize mass transfer resistance in gas, membrane, and liquid
- Contactor durability - Long-term membrane wetting in contact with solvent can affect performance
  - Improve membrane hydrophobicity
- Solids and impurities – Coal fines plugging gas flow inside fibers
  - Determine gas and liquid filtration needs
- Contactor scale up
  - Commercial equipment by experience company
  - Linearly scalable test equipment already in modular form
- Solvent Chemistry
  - Commercial solvents used

PEEK Membrane Can Meet Technical Challenges

- PEEK is “best in class” engineering plastic with exceptional thermal, mechanical, and chemical resistance
- Hollow fiber with high bulk porosity (50-80%), asymmetric pore size: 1 to 50 nm, and thus high gas diffusion flux
  - Helium permeance as high as 19,000 GPU
- Super-hydrophobic, non-wetting, ensures independent gas and liquid flow
- Structured hollow fiber membrane module design with high surface area for improved mass transfer





*1 GPU = 1 x 10^6 cm^3 (STP)/cm^2 • s • cmHg

PoroGen has Commercial Technology from Polymer to System

PEEK Fiber + Cartridge + Module = Separation System

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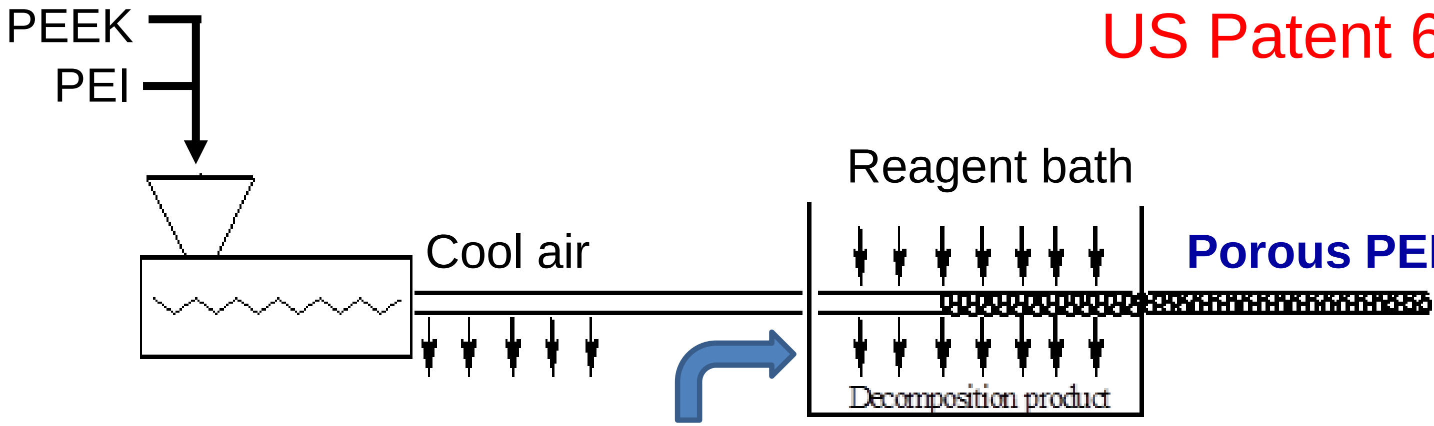
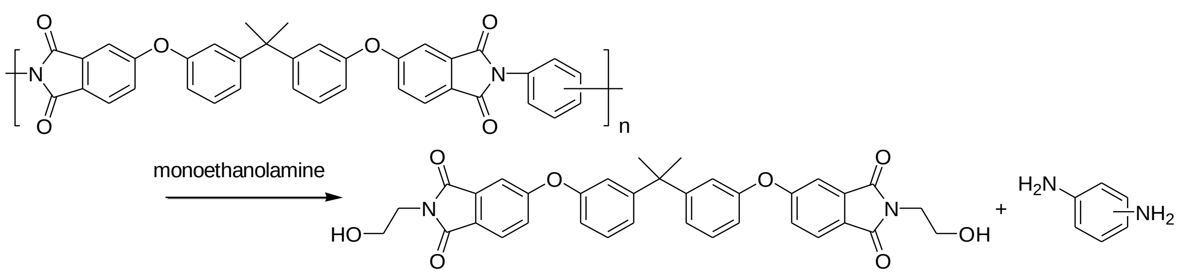
PoroGen Controls Pore Size and Volume, Fiber Diameters, Modify Surface and Flow Dynamics of Pressure Drop, Packing Density, Tortuosity

US Patent 6,887,408

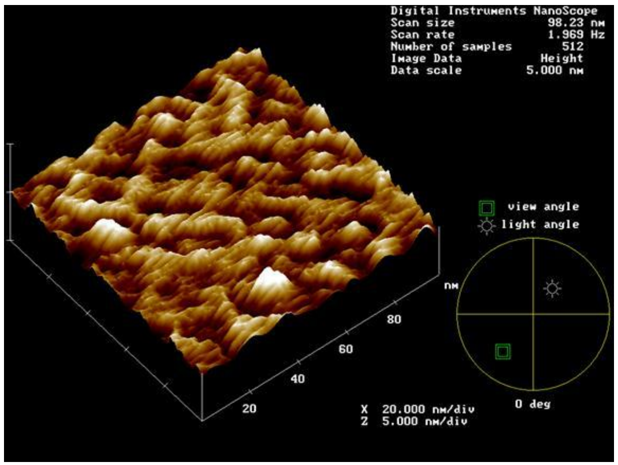




PEI = poly(ether imide)

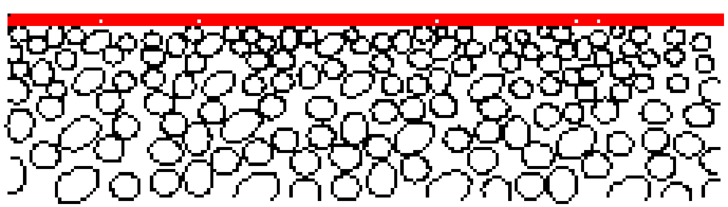
Two types of super-hydrophobic membranes under development

a) Nano-porous PEEK hollow fiber membrane



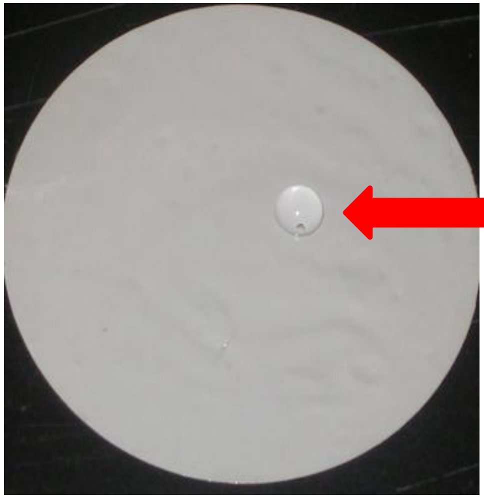
b) Composite PEEK hollow fiber membrane

Thin layer (0.1 μm) of smaller surface pores



Asymmetric porous structure

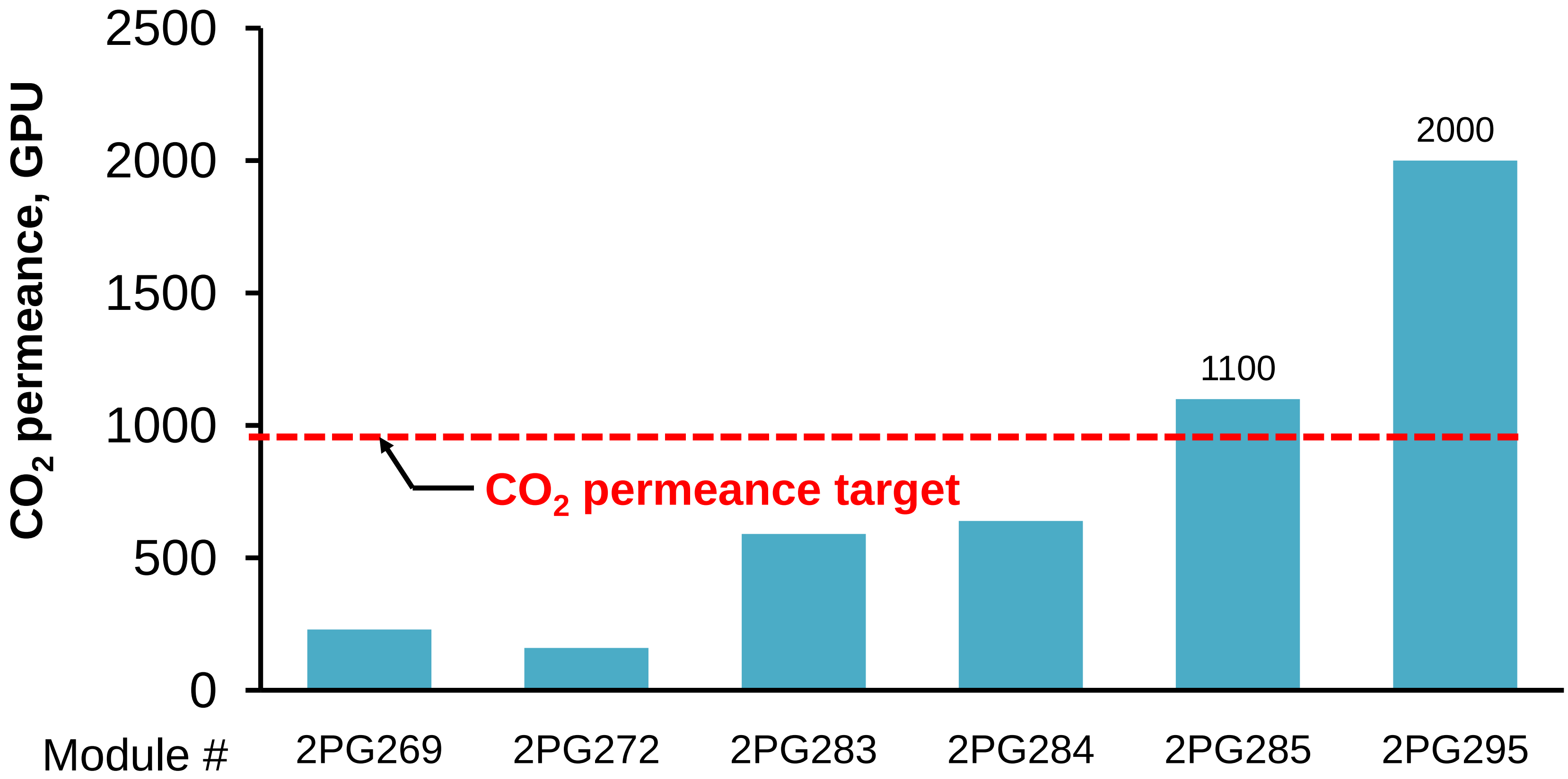
Super-hydrophobic surface not wetted by alcohol



Alcohol droplet

Membrane intrinsic CO_2 permeance exceeded initial target commercial performance

More than 30 modules constructed by PoroGen



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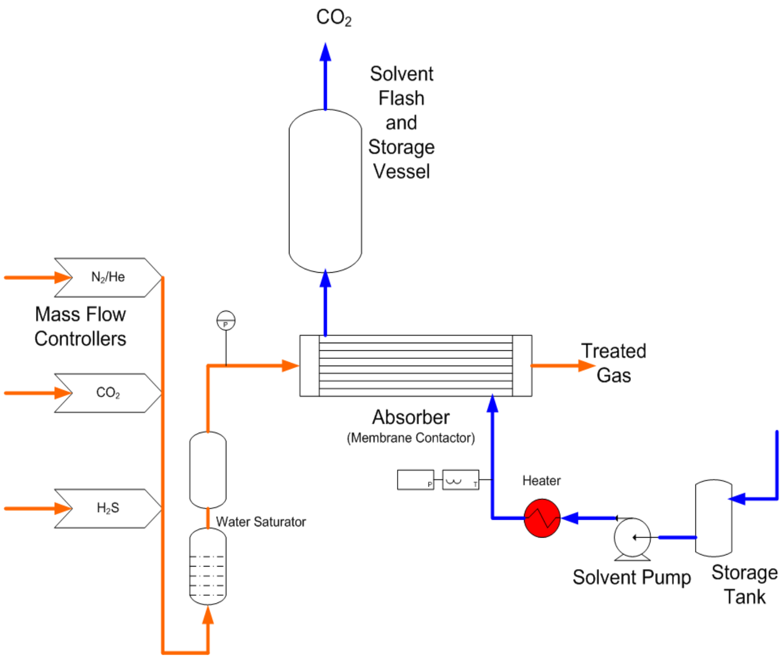
Performance Test Conditions

- Tested module performance can be linearly scaled to commercial size modules
- Simulated syngas tests in the lab
- Actual gasifier feed from GTI FFTF runs
- Physical solvents – Morphysorb™, Selexol™, water, and methanol
- Design of experiments test matrix

Membrane Contactor Bench Unit



- 2 inch modules
- 14 gallon/hr solvent flow

0.6 MMscfd N_2/CO_2 mixture
1000 psig, 25 to 75 ºC

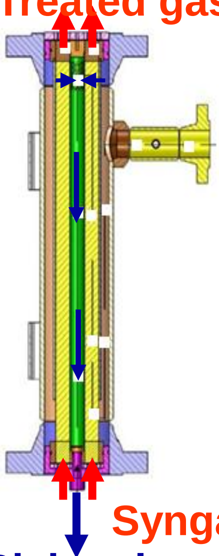
- Moisture addition and measurement
- Fully instrumented and computer controlled.

Typical Performance Data

Total Gas Flow, SLPM	Solvent Rate, L/min	Solvent T, ° F	Gas P, psi	In CO_2, mol%	CO_2 Removal, %
-	+	+	500	39.23	**98.5**
+	-	+	500	41.4	66.0
-	-	+	500	38.0	19.4
+	+	+	500	39.4	41.8
-	-	-	500	38.9	**99.3**
+	-	-	500	43.9	**98.3**
+	-	-	500	43.0	**97.2**

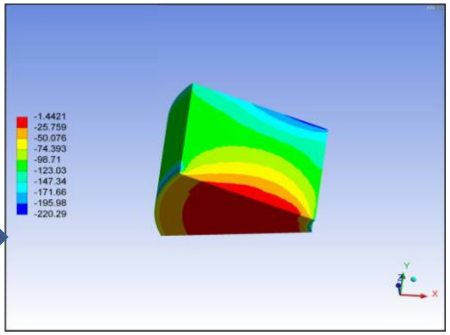
- CO_2 removal greater than 90% demonstrated
- Material balances within 3% for related high pressure testing
- Mass transfer is liquid side controlled. Further optimization of hollow fiber structured packing through computer controlled helical winding is on-going

Membrane module design and scale-up to 8 inch commercial scale



8 inch design model

- Design of commercial size, high-pressure, syngas CO_2 capture module completed
- Design validated through CFD modeling
- Scaling up from 1 m^2 to 100 m^2 (8-inch commercial module)
- Production of 8” diameter module on commercial equipment established


Tubesheet CFD stress analysis

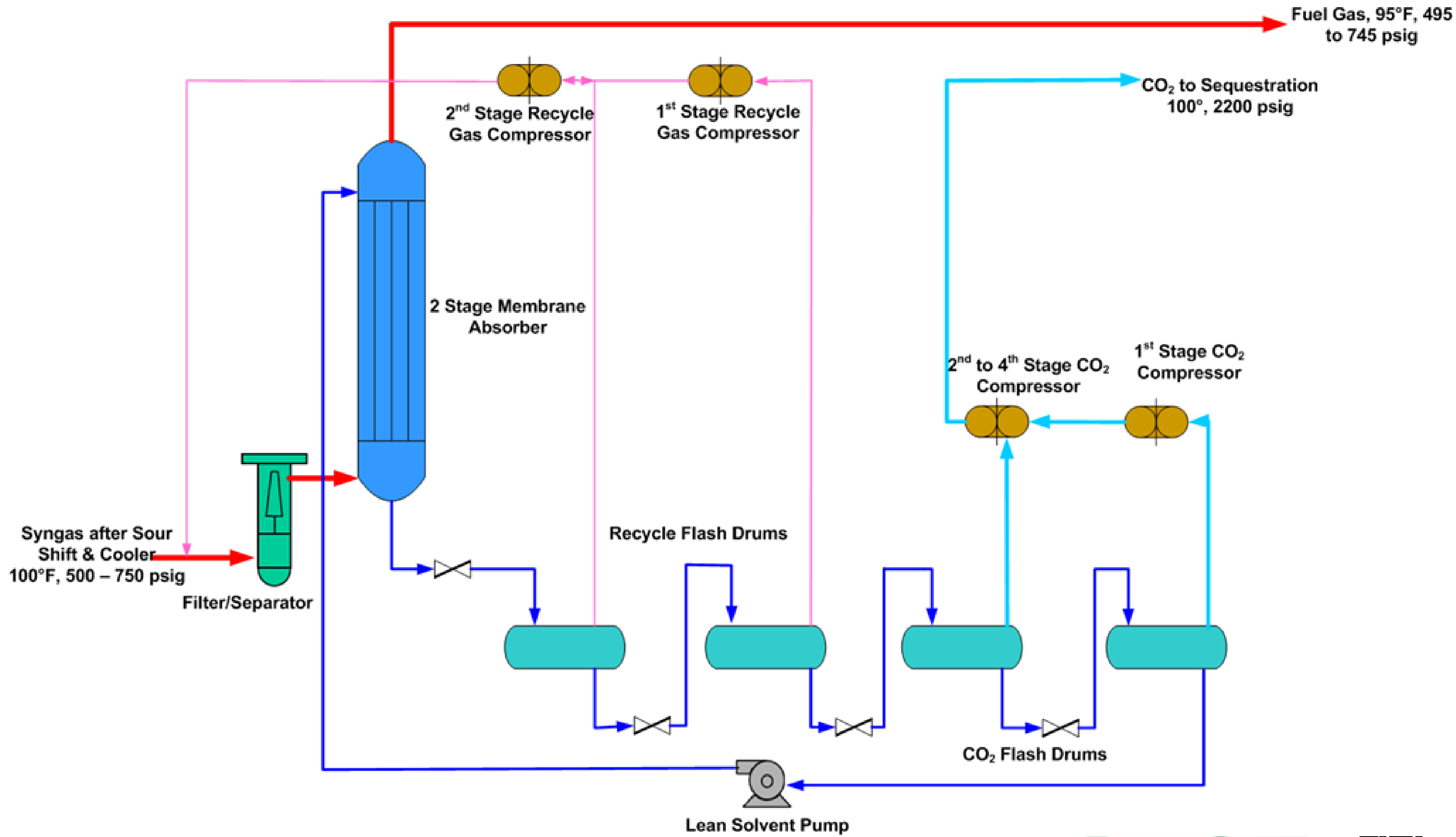

Cartridge tubesheet for Ø8” x 60” long module


Equipment to produce 8-inch modules

Membrane Process Design and Economic Evaluation

- 90% carbon capture, 95.1% pure CO_2, 95.4% pure H_2
- 8-inch-diameter, commercial-scale membrane contactors
- Measured mass transfer coefficient
- Process model based on detailed mass and energy balance and solving detailed transport equation in the liquid phase
- Utilized DOE Cost and Performance Baseline for Fossil Energy Plants (DOE-NETL-2007/1281) Case Number 2 by replacing the CO_2 control system with GTI's membrane contactor technology
- Dollar-Year Reporting Basis: 2007 $
- Levelized-Cost of CO_2 Transport, Storage & Monitoring: $4.05 / ton CO_2

Process Flow Substituted Membrane Contactor for Columns



Estimated LCOE

Cost	LCOE ($/MW)		
	Case 1	Case 2	Membrane Contactor ($100/m^2)
Capital	$45.28	$59.65	$49.35
Fixed O&M	$6.05	$7.50	$6.77
Variable O&M	$7.51	$9.35	$8.45
Coal	$19.36	$22.78	$20.58
CO_2 TS&M	$0	$4.36	$3.89
Total	$78.20	$103.64	$89.04
% Increase from Case 1		32.5%	13.9%

Compare with Project Goal

- 90% CO_2 capture can be achieved with the membrane contactor technology using physical solvent
- LCOE increase of 14% from baseline plant without CO_2 capture compared with a goal of 10% increase.

Plans to Complete Project

- Complete solvent testing with H_2S and improved membranes
- Performance and life testing with real gasifier feed
  - Test unit built and ready
  - Waiting for next gasifier run in early Oct. 2011
- Refine process and economic model
  - Based on gasifer test results

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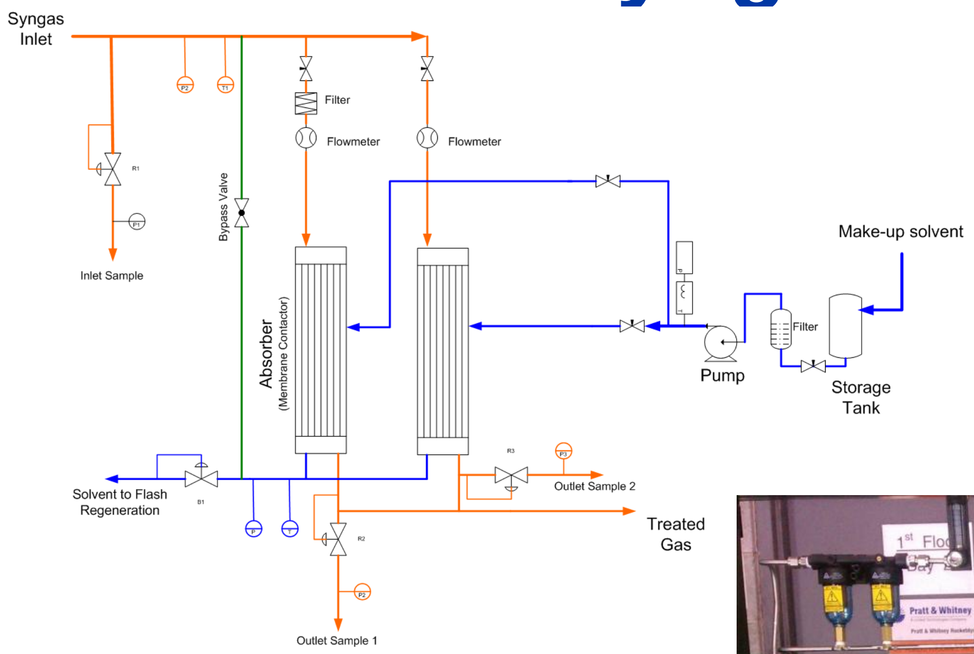
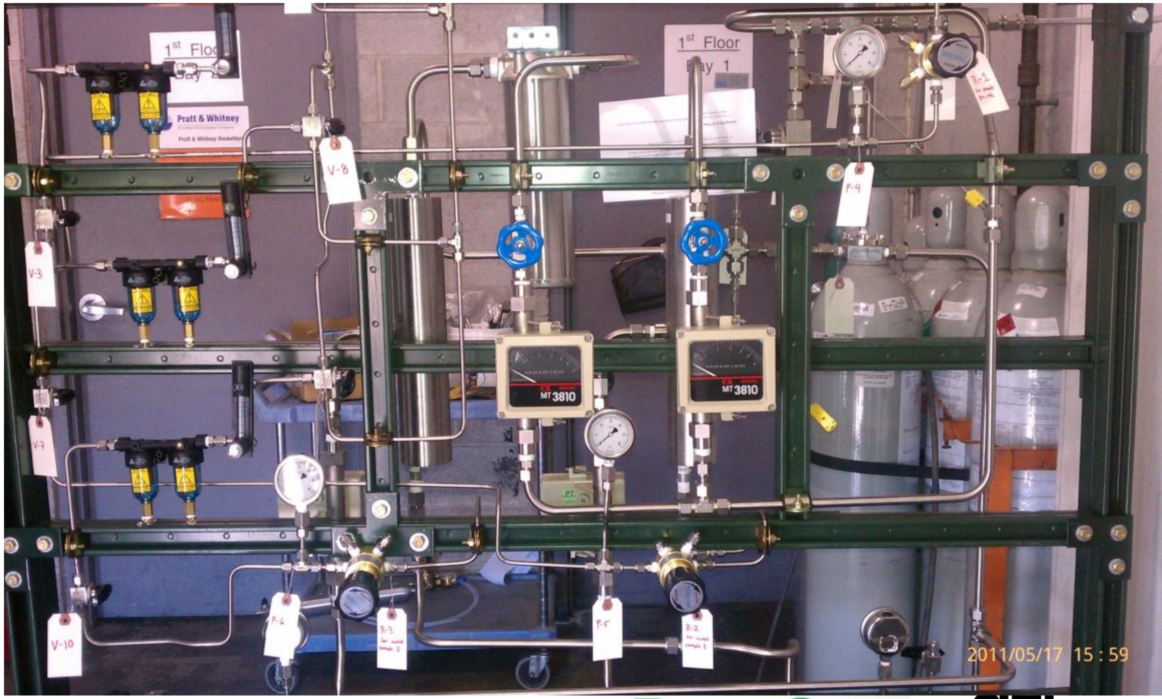
Syngas Test Unit





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Steps After Current Technology Development Project

- Scale-up membrane module production
  - 8-inch to 12/16-inch-diameter modules to improve economics
- Membrane stability, durability, life
- Detailed process and economic modeling using plant data
- Technology implementation timeline after this project

Time	Development	CO_2 capture, Ton/day	Module diameter, in.	Projected # of modules*
By 2013	2.5 MWe pilot-scale	50	8	5
By 2016	25 MWe demo scale	500	8 or 16	50 or 13
By 2018	550 MWe Commercial	11,000	8 or 16	1,000 or 250

Summary

- Demonstrated the feasibility of using membrane contactor technology for CO_2 capture from high pressure syngas
- 90% CO_2 removal from simulated syngas demonstrated
- Built a basic process and economics model
- Commercial size membrane contactor module designed
- Economic evaluation based on membrane contactor lab testing data indicates a 14% increase in LCOE

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